Title: Climate and Rivers

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Abstract

Over the last few decades as hydrologists have slowly raised their line of sight above the watershed boundary, it has become increasingly recognised that what happens in the atmosphere, as a major source of moisture for the terrestrial branch of the hydrological cycle, can strongly influence river dynamics at a range of spatial and temporal scales. Notwithstanding this, there is still a tendency for some in the river research community to restrict their gaze to the river channel or floodplain. However Geoff Petts, the person to which this special issue is dedicated, understood well and widely encouraged a holistic view of river catchment processes. This included an acknowledgment of the role of climate, in its broadest sense, in shaping what happens within and without the river channel. The purpose of this paper therefore is to offer a broad overview of the role of some aspects of climate science in advancing knowledge in river research. Topics to be addressed include the role of climate in influencing river flow regimes, a consideration of the large scale climate mechanisms that drive hydrological variability within river basins at inter-annual to decadal timescales and atmospheric rivers and their link to surface hydrology. In reviewing these topics a number of key knowledge gaps have emerged including attributing the causes of river flow regime changes to any one particular cause, the non-stationary and asymmetric forcing of river regimes by modes of climate variability and establishing links between atmospheric rivers, and terrestrial river channel processes, fluvial habitats, and ecological change.

Keywords: climate and rivers, hydrological variability, river flow regimes, atmospheric rivers, climate variability, ENSO, hydroclimatology

1. Introduction

Included within the multiple framings of how rivers might be examined is climate. The study of rivers in a climate context is generally referred to as hydroclimatology, the main purpose of which is to understand the degree of dependence of hydrological cycle processes on climate (McGregor, 2017). Often simply described as the average weather of a location, climate of course is more than a statistical entity. Rather climate, as defined by Bryson (1997), is the thermodynamic/hydrodynamic status of the global boundary conditions that determine the concurrent array of weather patterns. Climate seen in this way is clearly important to rivers and their physical and ecological processes as the climate of a location, including its mean, variability, trend and extreme characteristics, provides the setting for a range of possible hydrological responses. Further, as climate is non-stationary (Litzow et al., 2018; Ouarda,et al., 2019; Razavi et al., 2015; Rodriguez-Fonseca et al., 2016), the relationship between climate and river systems may alter over time, such that there may be no true hydrologically normal state in river systems. Moreover climate, embodying the thermodynamic/hydrodynamic setting of a place, may change from near instantaneous to millennial time scales, such that river systems are in a continued state of climate-dependent flux, all other factors such as geological/tectonic and anthropogenic influences being equal. Such climate river flow associations have been conceptualised by a range of researchers (e.g. Bhagwit, 2014; Hannah et al., 2014; Kingston et al. 2006; Vihma et al., 2016) with conceptual models as presented in Figure 1 useful in terms of not only visualising the cascade of processes linking the atmosphere with the river basin in terms of drivers, moderators and responses, but serving as an organisational framework for research on climate river system linkages.

Because of the enormity of climate for river systems and its role as one of a multitude of stressors on rivers at a range of scales (Best, 2019), the purpose of this paper is to briefly review recent literature regarding the relationship between climate and river flow regimes, the extent to which hydrological variability, principally river flow, is dependent, at the inter-annual to decadal timescales, on modes of climate variability, and the significance of atmospheric rivers for extreme hydrological events. The justification for this choice of topics is partly personal related to the author’s working relationship with Geoff Petts, to whom this special collection of papers is dedicated. Geoff was always curious about the role of climate in fluvial and ecological processes and it seems fitting that this review touches upon some aspects of climate and river relationships which he was interested in, or would have become acquainted with if time had allowed.

Personal justifications aside, the fact that river flow regimes are fundamental determinants of the structure and function of river ecosystems, and any acute or chronic climate disturbances exacted on flow regimes will have fundamental impacts on the ecological and fluvial processes in rivers, provides just reasoning for addressing climate and river flow regime relationships. Similarly, climate driven hydrological variability, finding its origins in periodic perturbations of ocean and atmosphere circulation patterns, holds implications for the magnitude and frequency characteristics of catchment scale processes. Moreover understanding the link between large scale climate mechanisms operating at the intra-seasonal to decadal time scales may lay the basis for medium to long range hydrological forecasting, with benefits accruing in terms of water resources and river system management. Lastly, a consideration of atmospheric rivers, as a relatively new concept in hydroclimatology and atmospheric science, is vindicated on the grounds that much remains to be learned about the impact of this phenomenon on hydrological processes and extreme events. Of course, other topics could have been reviewed here such as climate and river thermal regimes and climate based sub-seasonal to seasonal hydrological forecasting. However these topics probably deserve standalone reviews and accordingly will not be touched upon.

The remainder of this paper is organised into three main sections namely river flow regimes, climate variability and atmospheric rivers. The paper is brought to a close with a brief synthesis and conclusion.

2. River Flow Regimes

The concept of river flow regimes has a long history in river science, applied to describe the seasonal distribution of river flow over the hydrological year in natural river systems (Harris et al., 2000). Flow regimes are closely linked to climate and reflect the influence of the temporal and spatial distribution of precipitation, temperature and evapotranspiration on river flow, although drainage basin characteristics, such as physiography, geology and vegetation cover, moderate this relationship (Beckinsale, 1969). Aside from being a convenient concept for capturing the complexity of flow response to a range of natural controls, flow regimes are critical regulators of river channel and flood plain geomorphic processes, ecohydrological habitats and biodiversity in fluvial ecosystems and river thermal regimes (Garner et al., 2014; Hannah et al., 2004; Harris et al., 2000). Flow regimes also bear implications for a range of human activities and the risk arising from hydroclimatological hazards (McGregor 2015; 2017). Generally the five components of flow regimes which are held to be climate sensitive and considered to directly [i]or indirectly influence fluvial related processes and ecosystems are magnitude, frequency, duration, timing, and rate of change (Poff et al., 1997). Given the continuing legacy of flow regimes as a concept in river science work focused on flow regime classification, observed changes in flow regimes and the impacts of climate change on flow regimes will be described in this section.

2.1 Flow Regime Types

As climate is considered a fundamental determinant of a river's flow regime much effort has been invested in developing flow regime typologies. In developing these, the underlying assumption is that the seasonal distribution of precipitation, temperature and evapotranspiration are reflected in the seasonal flow pattern, or in other words there's an association between climate region and a river flow's regime characteristics. Given this a number of attempts have been made to apply standard climate classifications to the development of flow regime categorisations. However as pointed out by Knoben et al. (2018), many climate classifications are bio-climatic in origin and lack hydrologically relevant details essential for a meaningful categorisation of flow regimes. For example Haines et al (1988), in an attempt to construct a global classification of flow regimes noted while the Koppen-Geiger climate classification was partially successful in predicting flow regimes with a matching of regime types with climate zone, there was a lack of specificity as any one flow regime could be found across a number of climate zones; 15 different global streamflow patterns were identified by Haines et al. (1988). Similarly in developing flow regime classifications for the United States a number of researchers have noted the inclusion of hydrologically relevant parameters improves the resulting regionalization (Addor et al., 2017; Berghuis et al., 2014; Pool et al., 2019).

To address the problem associated with applying standard climate classifications to flow regime categorisation Knoben et al. (2018) developed a hydrologically informed climate classification using three dimensionless climate indices, namely annual aridity, aridity seasonality and precipitation as snow. Acknowledging that there may be varying degrees of membership of a catchment to a particular climate class and therefore flow regime, as noted by Sawicz et al. (2011), they identified 16 flow regimes from the analysis of the covariant behaviour of the three aforementioned climate indices for 1,103 catchments (Figure 2). Across the 16 regimes three broad groups exist. One group comprising three regime types, similar with respect to the seasonality of aridity and importance of snow, are differentiated with respect to decreasing degrees of aridity and thus increasing average flow across the three regimes. A second group of six regimes, while comparable in terms of aridity and insignificance of snow are individually dissimilar with respect to aridity seasonality. Possessing like values for snow and seasonality, a third broad group of regimes is progressively less arid across its members. Consequently these regimes are characterised by high average and pronounced peak flows. Setting aside the details of the individual flow regimes an important conclusion of the Knoben et al. (2018) study is that hydrologically relevant indices are superior to climate classifications such the Koppen-Geiger scheme, when applied to grouping catchments and identifying similar flow regimes. Furthermore seasonal flow patterns progressively change along climate gradients such that there is a continuous/seamless spectrum of flow regimes, something previous flow regime categorisations based on climate classifications have not acknowledged because flow regimes types have been presented as mutually exclusive.

In an earlier attempt at deciphering the range of flow patterns at the global scale, Dettinger and Diaz (2000) used streamflow data from 1345 sites to not only derive a streamflow pattern typology but consider the dominant patterns in terms of their underlying driving climate dynamics. Published prior to the work of Knoben et al. (2018), the Dettinger and Diaz's (2000) work is refreshing as it tries to uncover the underlying climate processes that drive flow regimes. Four dominant modes of streamflow seasonality were uncovered by Dettinger and Diaz (2000) namely: (i) late boreal spring stream flow maximum, (ii) monsoonal mid-summer stream flow modes centred on July–August, (iii) a monsoonal late-summer streamflow mode centred on September and (iv) a boreal winter-to-spring stream flow maxima toward the headwaters of the aforementioned late boreal spring mode (i). Accounting for 70 percent of the total variance of stream flow seasonality these map broadly onto the 3-4 broad groups identified by Knoben et al. (2000). Further to identifying the four main geographical types, Dettinger and Diaz (2000) applied a K-means cluster analysis to derive a 10 category classification of the main shapes of mean monthly streamflow, some of which demonstrate clear flow peaks while others possess a relatively invariant seasonal flow pattern (Figure 3).

Although not focused strictly on flow regimes, the attempt by Beck et al. (2015) to produce global maps of streamflow characteristics is of interest as flow regime types may be inferred from these. In producing the maps five hydrologically relevant climate indices, along with a range of physiographic characteristics, were applied to an exploration of the association between the physical environment and streamflow characteristics as a basis for estimating flow characteristics in ungauged basins. The climate indices, which included an aridity index, precipitation seasonality, transformed mean annual precipitation, mean annual potential evaporation and potential evapotranspiration seasonality, were found to exhibit the strongest relationships with streamflow and were deemed as superior predictors of basin flow compared to physiographic factors (Beck et al., 2015). Other attempts at the global scale to produce information that paves the way for understanding climate – flow regime associations include that of Gudmundsson et al. (2018; 2019), Barbarossa et al. (2018) and Padron et al. (2017) who have produced a range of quality controlled time-series indices relevant to establishing the nature of a river's flow regime. Understandably at the regional or national level there are many variations on the broad flow regime types found at the global level because, as noted above, regime types exist on a continuum of climate gradients. It is therefore not surprising that in studies that focus on individual countries a variety of flow regime types can be found. For the United States Archfield et al. (2014) identified flow pattern groupings at a number of levels with increasing degrees of differentiation across two to eight flow regime groups. That variants on the eight flow regimes at the level of the United States exist is manifest in the work of Lane et al. (2017) who identify eight natural flow classes representing distinct flow sources, hydrologic characteristics, and catchment controls over rainfall-runoff response. Across Canada Jones et al. (2014) have identified 10 flow regime classes, as many as Dettinger and Diaz (2000) at the global level. A spatial characteristic of the Canadian flow regimes is that some classes occur across Canada, whereas others show greater regional grouping. In explaining the mixture of spatial heterogeneity and clustering, Jones et al. (2014) point to the possible influence of the distribution of hydrological stations across Canada, many of which were installed for flood forecasting and frequency analyses. Further to the south in Haiti three groups of hydrological regimes have been revealed by Gaucherel et al. (2016) with these characterised by relatively stable flow rates, periodic and strongly seasonal flows and unstable flow rates. For the United Kingdom Bower and Hannah (2002) identify four flow regimes which are essentially variants of global level flow patterns 2 and 3 of Dettinger and Diaz (2000) and flow types 10, 15 and 16 of Knoben et al. (2018) with these reflecting the seasonal distribution of important hydroclimatic controls such as precipitation and temperature/snowmelt. Seven distinct flow regimes have been revealed by Piniewski (2017) for Poland with four associated with the Polish Plain, one restricted to the uplands, and 2 typifying mountain environments. At the European scale an insight into the nature of flow regimes has been provided by Hall and Bloeschl (2018). Based on an analysis of 4105 water level stations they identified six spatially consistent regions with distinct flood seasonality characteristics. For the Huai river basin in China, Zhang et al. (2012) have identified six classes of natural flow patterns – low or high discharge, stable or variable, perennial or intermittent, predictable or unpredictable. In the Southern Hemisphere it would appear that a comprehensive classification of flow regimes has only been realised for Australia where Kennard et al. (2010) have recognised 12 distinct flow regime types which differ mainly in the pattern of seasonal flow, degree of flow permanence and variations in flood magnitude and frequency. The greatest variation of flow regimes in Australia is found along the east coast where the transition from tropical, through sub-tropical to mid-latitude temperate climate types progressively nudges the timing of the peak flow southwards towards the austral winter months.

2,2 Observed Changes in Flow Regimes

Increasingly shifts in flow regimes are being investigated as indicators of change, especially in relation to that associated with global warming as this has the potential to alter the spatial and temporal patterns of hydrologically sensitive climate variables such as precipitation, temperature and evapotranspiration. While some evaluations use empirical data to test for trends in regime type over the last several decades, others apply numerical climate and hydrological models to ascertain the nature of future flow regimes.

In a study that explored changes in observed western North American streamflow timing for the period 1948-2008, Fritze et al. (2011) found a shift in streamflow to earlier in the water year, most notably for those basins with the largest snowmelt runoff component. In contrast, coastal rain-dominated and some interior basins demonstrated a move to later timing with higher temperatures in January and March across the study region, as well as precipitation shifts at the sub-regional level accounting for the alteration of streamflow timing. Particularly pertinent in the context of climate driven changes to flow regimes was the swing from snowmelt to rain dominated flow regimes over the study period. Near-natural flow regimes for the United Kingdom over the period of 1968 – 2008 have been investigated for change by Hannaford et al. (2012). Results indicate a complex pattern of regional and seasonal variation with some shift in regimes mapping onto altered patterns of rainfall and hence increased winter and autumn runoff and high flows and diminished spring flows. Little persuasive evidence was found for any changes in summer flows. Importantly, Hannaford et al. (2012) emphasise the dependence of some results on study period and caution against upscaling the results from small drainage basins to the regional scale because of the spatial heterogeneity of observed flow regime trends. In nearby Scandinavia Matti et al. (2017) have found changes in flood seasonality over the last century as demonstrated by decreasing trends in summer maximum daily flows and increasing winter and spring maximum daily flows. Further, and as for the case of western North America (Fritze et al., 2011), it is likely that temperature driven shifts from snowmelt to rain dominated flow regimes account for the observed alterations in annual flood occurrence and timing (Matti et al., 2017). At the European scale Blöschl et al. (2017) point to a possible climate change related signal in flood regimes noting that earlier spring snowmelt floods across northeastern Europe are a consequence of higher temperatures, while later winter floods around the North Sea and some sectors of the Mediterranean are likely to be associated with delayed winter storms with earlier soil moisture maxima driving earlier winter floods in western Europe.

Using observed flow data for the Selangor River in Malaysia, Seyam et al. (2015) demonstrate that while negligible changes in mean annual flow were found between 1961 and 2010, the maximum annual flow generally increased while the minimum annual flow significantly decreased along with increases in flow variability and a number of high and low flow warning metrics. Disappointingly no climate based explanation is tendered for the observed changes. In contrast for the Pamir Alay region of Central Asia, Chevallier et al. (2014) attribute observed changes in river flow regimes to the homogeneous upward trend of air temperature and associated changes in the location, elevation and orientation of snow cover.

2.3 Flow Regime Change and Climate Change

In general, the burgeoning number of climate change and river flow regime studies use hydrological simulations driven by hydrologically relevant climate variables from climate models for a range of future emission scenarios or representative concentration pathways (RCPs) (Cui et al., 2018; Schneider, 2013; Soncini et al., 2015; Zhou et al., 2018). The output from the hydrological simulations is usually in the form of a number of direct or derived indices of hydrological alteration (Ekstrom et al., 2018; Gao et al., 2018; Pumo et al., 2018; Richter, 1996). For example in an assessment of the likely impacts of climate change on flow regimes for eleven representative large river basins covering all continents Eisner et al. (2017) applied an ensemble of nine regional hydrological models driven by climate projections derived from five global circulation models under four RCPs. Although they found only slight changes in the pattern of seasonal flow for the majority of river basins, climate change projections point to a possible acceleration of the present seasonality pattern with increases (decreases) in high (low) flows. They also note that for some basins no robust conclusions could be drawn because multiple projections signify opposing changes that nullify any net effect. Similarly in an analysis of the impact of climate change on flow regimes in one of Iceland's deglaciating basins, Mackay et al., (2019) note the difficulty to draw clear conclusions about the fate of flow regimes because of the uncertainty associated with distinct parts of the modelling chain that links numerical models of climate and glacio-hydrology. That models clearly play a role in the conclusions arrived at regarding climate change impacts on flow regimes point to the need for inter-model comparisons such as being achieved through the Sectoral Impact Model Intercomparison Project (ISIMIP) (Rosenzweig et al., 2017) and Coupled Model Intercomparison Project (Arnell et al., 2016; Ferguson et al., 2018).

An assessment performed by Schneider et al. (2013) for European flow regimes found the potential for climate change to alter seasonal flow patterns to be significant. Of the broad regions across Europe Schneider et al. (2013) highlight the Mediterranean as being particularly exposed to climate change because of a likely wholesale reduction of precipitation across the year. Equally the boreal zone of Europe is considered at risk to fundamental changes in flow regime because of climate change related alterations to snowmelt, and precipitation and temperature increases, the consequence of which will be shifts from snow to rain dominated flow regimes and a progression of the seasonal flow peak to earlier in the water year. For the European temperate zone, Schneider et al. (2013) indicate the impacts on flow regimes could intensify with the increasing continentality of the climate. As for the boreal zone of Europe, the impacts of climate change on flow regimes in British Columbia appears to be similarly tied to the fate of winter snowpacks and rain to snow precipitation ratios as demonstrated by Ul Islam et al. (2019) based on the analysis of the output from a process-based hydrological model driven by an ensemble of 21 statistically down-scaled simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) group of models under RCP 8.5. They note that close to half of the Fraser River Basin transitions from a snow-dominated runoff regime in the 1990s to a primarily rain-dominated regime in the 2080s. Further they suggest that an increased frequency of land-falling atmospheric rivers is likely to account for the predicted nival to a nival-pluvial hydrologic regime transition by the 2080s. For the Upper Indus Basin, Soncini et al. (2015) use a hydrological model driven by climate model output under RCP2.6, RCP4.5, and RCP8.5 to assess changes in flow regime to the end of the current century. Under all RCPs and up until the mid-century, flows are predicted to increase. In an assessment of the Niger River's response to climate change Angelina et al. (2015) forced a Soil and Water Assessment Tool (SWAT) model of the Niger River with the output from nine regional climate models under the SRES A1B emissions scenario. Changes in flow regime characteristics were found to be equivocal with little statistical evidence for significant systematic shifts in flows for the periods 2026-2050, 2051-2075 and 2076-2100 compared to the present. This contrasts with the unequivocal findings of a shift in the flow regime for the same river found by Yang et al. (2017). Admittedly these results are for a different time domain and emissions scenarios compared to that used by Angelina et al. (2015), which may well explain the contrasting findings. For the United States Zhou et al. (2018) adopt a different tact in assessing climate change driven alterations to flow regimes by testing the assumption that the cumulative distribution functions of flow for regulated rivers will be less sensitive to climate change compared to natural flows. They found significant shifts to earlier dates in the seasonal regulated flow for 40 percent of the hydrological units for the western United States under the case of climate change with noticeable changes in flow sensitivity for spring, winter and summer regulated flows, albeit less than that for natural flows.

In addition to the application of indices of hydrological alteration in the analysis of climate related changes to flow characteristics Fowler and Wilby (2010) and Zielgler (2005) have introduced the concept of climate detection time to discern emergent climate signals in river flow regimes.

2.4 Flow Regime Change Attribution

While the role of river regulation in altering flow regimes has been mostly assessed independent of possible climate influences, a number of useful studies are emerging that address the attribution problem by posing the question ‘are observed changes in flow regimes attributable to climate change or other human influences?’. Some so-called attribution studies point strongly to the role of climate factors in determining flow regime changes (e.g. Hall et al., 2014; Harrigan et al., 2014; Mertz et al., 2012). However others emphasise the significance of non-climate factors other than river regulation. For example Yang et al. (2012) find for the semi-arid Hailiutu River in Northwest China that flow regime changes are more related to the historical trend of land use driven by government policy, rather than climate. Similarly for the case of snow dominated regions, Arheimer et al. (2017) contend that hydropower regulation is a key driver of flow regime change and is more important than future climate changes. Human as opposed to climate influences on flow regimes also appear to be important for some Northern European sub-Arctic rivers (Bin Ashraf, 2016). Evidence of human related non-climate forcing of regime changes has also been put forward for the Northern Rocky Mountains by Arrigoni et al., (2010) who found that direct anthropogenic modifications of the river basins have altered the flow regimes to a much greater extent than regional climate change. However in stating this, Arrigoni et al. (2010) note that a slow variation of annual discharge amount, well beyond the inter-annual timescale, may be indicative of an underlying hydroclimatological cycle; with regard to this the Pacific Decadal Oscillation may well be a possible candidate (see next section). As opposed to using the entire length of a hydrological record some workers have considered the detection and attribution problem for distinct phases of river basin development. For example Li et al. (2017) for the Mekong River show the dictation of changes in streamflow regime are dependent on human interference especially in what they call a post-impact period beginning around 2010. Similarly for the Allegheny River in the United States, Akbari et al. (2019) demonstrate the progressive dominance of land use change over climate influences on flow regimes over three periods, namely near natural (1940-1955), low impact (1956-1966) and high impact (1967-2014).

3. Modes of Climate Variability and River Flow

Largely through research undertaken by hydroclimatologists it has become clear over the last 10 – 15 years that variations in atmospheric and oceanic circulation patterns, beyond the weather time scale and often referred to as modes of climate variability (de Viron et al, 2013) are important determinants of river flow variability (McGregor, 2017) and thus a range of fluvial (Dibike et al., 2018; Lawler et al., 2003; Nilawar et al., 2019; Shrestha et al., 2018) and ecohydrological processes (Gutierrez-Fonseca et al., 2018; Leigh, 2013; Scarabotti et al., 2017). Given this, the purpose of this section is to outline what is meant by climate variability in a hydrological context, briefly introduce the broad approaches adopted in assessing climate river flow associations and present the evidence for links between a range of modes of climate variability and river flow. The justification for this is by understanding the impacts on hydrological variability of large scale multi-time scale variations of ocean and atmosphere circulation patterns (Figure 1), a better understanding of fluvial and ecohydrological processes can be gauged. Such an understanding could lay the basis for forecasting river flow and associated fluvial and ecohydrological impacts at the sub-seasonal to seasonal (S2S) time scales (Emerton et al., 2016; Pappenberger et al., 2015; Neumann et al., 2018; Wetterhall and Di Giuseppe, 2018)

3.1 Modes of Climate Variability and Approaches to Investigation Climate River Flow Associations

Modes of climate variability are generally understood to be quasi-periodic variations in ocean and atmospheric circulation patterns that possess an oscillatory behaviour. climate variabilityA range of modes of climate variability (Kuchasrski et al. 2010; McGregor, 2017; Sheridan and Lee, 2015; de Viron et al., 2013) have been identified as potential drivers of intra-seasonal to inter-annual river flow variability (Dettinger and Diaz, 2000) some of which are presented in Figure 4. As noted by McGregor (2017) a large number of studies that assess the association between modes of climate variability and hydrological outcomes, whether they be stream flow, or a range of groundwater or lake hydrometrics, adopt a blind statistical approach with little reference to physical processes; analyses in the so-called frequency domain (e.g. spectral and wavelet analyses) are the main offenders. Because such studies are unhelpful in understanding the cascade of processes that link atmosphere-ocean circulations patterns and variations in the terrestrial branch of the hydrological cycle they will not be touched upon here. That aside, assessments of the impact of climate variability on local to regional hydrology usually follow an environment to circulation (EC) or circulation to environment (CE) approach (Yarnal, 1993). The former focuses on initially identifying hydrological events of interest followed by an examination of the ocean-atmosphere processes leading up to the event(s) with the hope that anomalous climate patterns/processes can be uncovered; analyses of composites of climate anomaly fields such as atmospheric pressure, precipitation, sea surface temperature and wind vectors are often at the core of the EC approach. In contrast the CE approach usually begins with an *a priori* classification of atmosphere-ocean states as described by one of many circulation indices or atmosphere-ocean circulation patterns/classifications comprising a number of categories with eventual establishment of whether an increased likelihood of a given hydrological anomaly is associated with any one given state or pattern. A common CE approach to establishing the relationships between river flow variability and modes of climate variability is to assess the degree of association between a teleconnection index (Dahlin and Ault, 2018; Kucharski et al., 2010), which models the temporal behaviour of an individual mode of climate variability, and a time series of river flow (McGregor, 2017).

3.2 Modes of Climate Variability in the Pacific Basin and River Flow

Atmosphere-ocean circulation anomalies in the Pacific Basin, in the form of El Nino Southern Oscillation (ENSO) events and the contrasting phases of the Pacific Decadal Oscillation exert far reaching influences on regional precipitation and temperature patterns beyond the Pacific (McGregor and Ebi, 2018) and thus possess the potential to induce variability in hydrological systems; recent descriptions of the ENSO and PDO phenomena can be found in Cai et al., (2015), Geng et al., (2019), Newman et al., (2016) and Wang et al., (2016). This is apparent for a number of regions and specific catchments as established by both EC and CE approaches. For example for western regions of the North American continent the PDO has been found to influence inter-annual stream flow variability and runoff trends across western Canada (Bawden et al., 2015) and the Pacific coast of the United States (Bhandari et al., 2018). For the same region PDO effects on flood magnitudes also exist with higher magnitude floods found to occur more frequently during a negative, as opposed to a positive PDO phase, in the upper Fraser River, Columbia River and North Saskatchewan River Basins (Gurrapu et al., 2016). Further north over the west Canadian Arctic, the frequency and positioning of summer and winter anticyclonic blocking and trough patterns over the Pacific Ocean and western North America, as moderated by the PDO and ENSO, are critical determinants of hydroclimatic variations and ice melt -dominated stream processes (Newton et al., 2014a; 2014b). Across the south-eastern United States Clark et al. (2014) and Risko and Martinez (2014) have also shown ENSO and PDO influences on streamflow while Sagarika et al. (2015) reveal strong regional effects on US stream flow variability by the PDO and inter-decadal variations in the Atlantic Basin. Beyond North America, hydrology related ENSO and/or PDO influences are also apparent for India (Panda et al., 2013); Chile (Rubio et al., 2010; Nunez et al., 2013), Brazil (Sahu et al., 2014), China (Ouyang et al., 2014; Peng et al., 2018) the United Kingdom (Folland et al., 2015) central Karakoram Himalayan region Veettil et al. (2016), Mexico (Lanza-Espino et al., 2011) and Australia (Liu et al., 2018; Shams et al., 2018). At the global level Su et al. (2018), based on an analysis of 916 of the world's largest ocean-reaching rivers for the period 1948-2004, found ENSO to be a significant driver of inter-annual river flow for 36% of the rivers analysed, with the PDO accounting for river flow variation for over 25 percent of the rivers. In a similar attempt to establish the hydrological importance of ENSO at the global level, Ward (2016) has shown partial dependency of flood duration and frequency on ENSO state with flood duration more responsive to ENSO anomalies compared to flood frequency.

3.3 Modes of Climate Variability External to the Pacific Basin and River Flow

Other modes of climate variability revealed as important for moderating hydrological processes include the Southern Annular Mode (SAM), the Indian Ocean Dipole (IOD), the North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and the Atlantic Meridional Oscillation (AMO). In the case of the SAM, influences are mainly restricted to the Southern Hemisphere where for New Zealand Li and McGregor (2017) demonstrate both geographical and seasonal dependence of river flow variability on the SAM. Using proxies of river flow, the hydrological importance of SAM for drainage basin processes has also been demonstrated for the southern half of South America and Tasmania Australia (Allen et al. 2015; Araneo and Villalba, 2015; Lara et al. 2015; Munoz et al., 2016). That ENSO does not act alone as a determinant of hydrological variability at the inter-annual time scale is clear for Australia and southern Asia where the Indian Ocean Dipole, as manifest via an east to west seesaw in Indian Ocean sea surface temperature anomalies, displays significant interactive effects with ENSO. In the case of flood magnitude and frequency across Australia, summer and spring flood variability is closely tied to ENSO activity whereas significant impacts are imparted on autumn and winter floods by the IOD. For the Ganges- Brahmaputra Basin, Pervez and Henebry (2015) have shown an ENSO warm phase in tandem with a positive IOD event increases the likelihood of drought and reduced flows while co-occurrences of a La Nina or ENSO cool phase and negative IOD events are conducive to major flooding. Similarly Fournier et al. (2015) and Sarma et al. (2015) point to the importance of IOD events for moderating sediment fluxes and freshwater discharge to the Bay of Bengal via the Ganges- Brahmaputra river system. Along the eastern seaboard of the United States and across Western Europe, ocean-atmosphere influences on inter-annual streamflow variations in are mainly attributable to the NAO and AO with possible moderation by the AMO. Winter atmospheric blocking and a predominance of northerly atmospheric flows and their impact on precipitation deficits produce anomalously low stream levels across Luthuania, Romania, Scandinavia, Spain and the United Kingdom (Birsan et a., 2015; Burt et al., 2016; Engstrom and Uvo, 2016; Hidalgo-Munoz et al.. 2015; Mihaila and Briciu, 2015; Rimkus et al., 2014). Confirmation of these relationships is found in a review of the links between large-scale circulation patterns and streamflow in Central Europe by Steirou et al. (2017; 2019). They find that NAO stream flow associations are strongest for the winter season with a dipole-like pattern across Central Europe such that north of the Alps and the Carpathians NAO – stream flow relationships are positive while to the south they are negative. Further Steirou et al. (2017) note the importance of the winter NAO state for the amplitude and timing of spring snowmelt as well as the varying importance of other modes of climate variability such as the Scandinavia (SCA) and the East Atlantic/West Russian (EA/WR) patterns. These findings resonate with those of Nobre et al. (2017) in relation to the influence of the NAO and EA patterns on extreme rainfall, flood occurrence, and flood damage across Europe. For the eastern US, stream flow demonstrates strong seasonal and NAO strength dependency (Coleman and Budikov, 2013; Sheldon and Burd, 2014). For floods across Europe and North America at large, Hodgkins et al. (2017) find the impact of the AMO on flood magnitudes to outweigh by far that due to long term trends.

3.4 Asymmetry and Non-Stationarity of Climate River Flow Associations

Implicit in the above discussion is the asymmetry of climate variability mode - stream flow associations such that the likelihood of major impacts on fluvial and ecohydrological processes and systems may be greater for a particular phase of a given mode of climate variability. In relation to this Dery et al. (2012) highlight the importance of the polarity of ENSO and PDO influences on inter-annual stream flow variability for the Fraser River Basin such that ENSO (El Nino) and PDO warm phases produce more marked responses than their cool equivalents (La Nina; PDO cool phase) a finding that has been corroborated by Gobena et al. (2013). In a similar vein Liang et al. (2014) have uncovered a non-linear/asymmetric response of the Mississippi River Basin to subtly different manifestations of ENSO warm events such that higher (lower) soil water levels, which bear implications for flood occurrence (Munoz and Dee, 2017), are associated with eastern (central) Pacific El Nino events. Similarly but at the global level, Liang et al., (2016) assessed the discharge responses to the central Pacific and eastern Pacific El Nino events for 30 of the world's largest rivers. They found North American rivers to have the strongest asymmetry. In contrast Australia's Murray River and Central Europe's Danube River possessed the strongest symmetry. Liang et al. (2016) also note a varied response pattern for rivers in Asia and Africa dependent on the stage of El Nino development. Such empirical evidence of the asymmetric impacts of the two El Nino types on hydrological processes as found by Dery et al. (2012), Gobena et al. (2013) and Liang et al. (2016) has been substantiated via atmospheric general circulation model simulations of the hydroclimatic response to idealised eastern and central Pacific El Nino events (Frauen et al., 2014). In a global study focused specifically on the identification of symmetric and asymmetric responses in seasonal streamflow to the El Nino and La Nina phases of ENSO, Lee, et al. (2018) found strong symmetric patterns only when rainfall and streamflow anomalies fell into above normal and below normal categories associated with either an El Nino or La Nina phase. Regions that were found to display a strong symmetric streamflow pattern, in response to contrasting ENSO phases, were north-western and southern US, north-eastern and south-eastern South America, north-eastern and southern Africa, south-western Europe, and central-south Russia. Asymmetric stream flow patterns were found where climate and stream flow anomalies are restricted to only one of the two phases of ENSO, particularly over much of the European continent, western Russia and western Asia. Such asymmetric streamflow responses to

ENSO phases mostly relate to the asymmetric response of atmospheric circulation patterns to El Nino events. For example the asymmetry of the hydrological response over China results from El Nino related anomalous circulation over the western North Pacific with anomalously strong (weak) Western Pacific Subtropical High activity during El Nĩno (La Nina) resulting in suppression (enhancement) of rainfall and thus streamflow (Gu et al., 2017; Hardiman et al., 2018).

An underlying assumption in early studies of the association between modes of climate variability and river flow was a time-invariant association between climate and hydrological variability with an associated tendency for investigators to model relationships between climate and hydrological variables as stationary properties. However with the extension of record lengths it has emerged that temporal inconsistencies or non-stationarities exist in climate river flow associations. An early example of this realisation was the discovery of the breakdown in the ENSO Indian Monsoon (IM) association, such that statistical models assuming stationary ENSO-IM rainfall relationships have been rendered ineffective over multi-decadal timescales. For example, Krishnaswamy et al. (2015) present evidence for the time varying importance of ENSO and the IOD as major drivers of the inter-annual variability of the IM. They found that while the influence of the IOD on the IM has strengthened in recent decades, ENSO's relationship with IM has weakened and become more uncertain. Srivastava et al. (2019) in noting the changing relationships between major modes of climate variability and the IM, point to the shift in the tropical climate in the late 1970s, especially the warming of the central Pacific and the Indian Ocean (IO), as the driver of this non-stationarity. Although not focusing of intra-seasonal to inter-annual river flow forecasting, the work of Dutta et al. (2018) bears implications for attempts to develop river flow prediction models for the IM region using teleconnection indices such as ENSO as the predictors. They found that a statistical time-varying prediction model for IM rainfall, which accounted for non-stationarity in ENSO/IOD/-IM associations, to be superior in performance compared to a time-invariant model that assumed stationarity. Similarly for Indonesia Yanto et al. (2016) note the implications for hydrologic predictability of non-stationarities in the inter-annual and multi-decadal variability of Indonesian rainfall which are modulated by the interactions between ENSO and the PDO.

For the North American continent there is also burgeoning evidence of hydroclimate non-stationarities as found for the major headwater tributaries of the Saskatchewan River basin where Razavi et al., (2015) suggest that stationarity might never have existed in the hydrology of the region. For Ontario and California, Ouarda et al. (2019) note AMO, ENSO and PDO related non-stationarities for rainfall intensity-duration-frequency relationships which bears implications for river flood management. For successful prediction of the level of salmon recruitment to Alaskan rivers Litzow et al. (2018) also highlight the importance of understanding the time-varying association between modes of climate variability and North Pacific Ocean climate. They identified the late 1980s as a period when predictions based on the covariant behaviour of the PDO and North Pacific Gyre Oscillation (NPGO) broke down most likely due a transition of Pacific Ocean sea surface temperatures from a cool (negative PDO) to warm (positive PDO) phase which influenced weather patterns in the region of the Aleutian Low. For the North Atlantic sector Rodriguez-Fonseca et al. (2016) have reviewed the evidence for forcing of climate by ENSO. Although concluding that the ENSO-Atlantic teleconnection is weak over the North Atlantic, they note the role of multi-decadal ocean variability in modulating the strength of teleconnections such that the time varying impact of ENSO on North Atlantic sector hydroclimate may create windows of opportunity for seasonal predictability.

3.5 Moderators of Climate River Flow Associations

It would be naïve to assume an uninterrupted, direct and blunt forcing of hydrological variability by modes of climate variability. This is because catchment characteristics in a variety of forms such as catchment geology, shape, vegetation and general hydrological state can modulate the impacts of climate on river flows at a range of timescales (Figure 1). Recognised for a long time (e.g. Beckinsale, 199) the so-called catchment filtering role (Andres-Domenech et al., 2015) is apparent in a number of studies of the impacts of climate on hydrological variability. For example, Garner et al. (2015) in reviewing a number of studies draw attention to the role of catchment antecedent moisture conditions and the presence of water stores and their response times in moderating the impacts of climate variability on floods and low flows. In relation to the hydrological impacts of ENSO Rice et al. (2017) found that ENSO streamflow relationships at the catchment scale are strongly influenced by precipitation timing and phase, forest cover, and interactions between watershed topography and geomorphology. In an interesting analysis of the role of climate in geomorphic development, Phillips and Jerolmack (2016) highlight how the self-organization of near-critical channels in river systems filter the climate signal, thus blunting the impact of extreme rainfall events on landscape evolution. As well as filtering the effects of climate variability on river flow, intermediate-scale environmental factors have been shown to play an important role in modulating the effects of modes of climate variability on the water level dynamics and the ecology of lakes (Griffiths et al., 2014; Molinas and Donohue, 2014).

4. Atmospheric Rivers

As a subject of theoretical and applied research, atmospheric rivers (AR) have gained considerable traction in meteorology and climatology and are emerging as a phenomenon of interest for researchers in hydrology, fluvial geomorphology and ecology because of their role in the generation of extreme hydrological events and thus their impact on fluvial and ecohydrological processes. Like terrestrial rivers, which are flows of freshwater in a channel confined by banks on either side, atmospheric rivers are corridors of atmospheric moisture concentration that originate from a moisture source, generally flow in an eastward direction eventually delivering their moisture in the form of rain or snow over a well-defined geographical area along the west coasts of the mid-latitudes (Figure 5). Originally identified in microwave satellite images as filaments of high total column water vapour and accepted as an important feature of the atmosphere over the last two decades, and popularly referred to as rivers in the sky (Ralph, 2017), atmospheric rivers have been formally defined by the American Meteorological Society as

"*A long, narrow, and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapour in atmospheric rivers is supplied by tropical and/or extratropical moisture sources. Atmospheric rivers frequently lead to heavy precipitation where they are forced upward—for example, by mountains or by ascent in the warm conveyor belt. Horizontal water vapour transport in the midlatitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere. Atmospheric rivers are the largest "rivers" of fresh water on Earth, transporting on average more than double the flow of the Amazon River*" (Ralph et al., 2018, p. 839).

Given their gravity for hydrological processes and their potential to determine catchment or regional flood frequency statistics, this section will provide a brief overview of AR formation, their climatology, the evidence for generation of extreme events and likely trends under climate change.

4.1 Origin of Atmospheric Rivers

Hatched as a notion in the 1990s, and possibly earlier albeit referred to using different terminology (Browning, 2018), AR were initially a contested concept because they were seen to bear a close relationship with warm conveyor belts (WCBs) and tropical moisture exports (TMEs) (Ralph, 2017), with some workers suggesting there was little distinction between these phenomena. Despite early misgivings about the concept AR have firmly bedded down in the minds of the atmospheric community as a distinct and important feature of the atmosphere possessing their own life cycle (Sodemann and Stohl 2013). Having said that it is acknowledged there is some geographical overlap between ARs, and TMEs and WCBs, and that the two latter phenomena may well be important for maintaining ARs (Ralph, 2017). That WCBs, a feature of mid-latitude cyclones, are important in AR generation is emphasised by Dacre et al. (2015) in a consideration of AR formation. They make the point that while moisture transport from distant subtropical latitudes can occur during AR events most extra-tropical precipitation is due to local or nearby moisture evaporation. Accordingly they contend that extra-tropical cyclones play a fundamental role in the formation of ARs and that a general misconception persists that narrow strands of high moisture content that manifest as so-called ARs are drawn into developing cyclones all the way from the tropics. Rather than tropical sources of moisture, they demonstrate that poleward transport of high concentrations of moisture, are the result of the continuous cycling of moisture within the cyclone itself (Dacre et al., 2015). Notwithstanding this a number of studies point to both modelling and empirical evidence for a tropical source of moisture for ARs (Eiras-Barca et al., 2018; Ramos et al., 2019; Scoccimarro et al., 2018) pointing to the likelihood that both near/local extratropical cyclone and remote, or a continuum of moisture sources (Bao et al., 2006; Cordeira et al., 2013), 'feed' AR.

4.2 Climatology of Atmospheric Rivers

The availability of a range of gridded climate data sets and re-analysis products has facilitated the development of AR climatologies at a number of geographical scales. Ordinarily based on applying an AR detection algorithm to one or more reanalysis data sets (e.g. NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) https://gmao.gsfc.nasa.gov/research/merra/ or the European Centre for Medium Range Forecasting (ECMWF) ERA-Interim - http://apps.ecmwf.int/datasets/), AR climatologies have been useful for establishing the physical, temporal and spatial characteristics of AR as well as their sensitivity to modes of climate variability at the intra-seasonal to seasonal time scales.

In an all season analysis of AR over the North Pacific, Mundhenk, Barnes and Maloney (2016) show that AR occur throughout the year but with AR preferred locations displaced northward and westward during the boreal spring and summer without an overall change in AR number. At the intra-annual to inter-annual time scales alterations in the mean state of the North Pacific due to ENSO and the Madden Julian Oscillation (MJO) are shown to either compound or negate the occurrence of AR as well generate seasonally dependent changes in AR spatial patterns. In a similar analysis for the North Pacific, but for winter land falling AR, Payne and Magnusdo (2015) found the largest number of land falling AR events occur in November with a systemic decrease over the subsequent winter months. Further the largest (fewest) number of land falling events were associated with El Niño (La Niña) with the average latitudinal position of AR shifting equatorward during El Niño events. At the decadal time scale, Liu, Ren and Yang (2016) highlight the possible importance of the Pacific Decadal Oscillation in influencing AR trajectories while Gershunov et al. (2017) note important associations between Pacific sea surface temperatures and AR frequency which may bear implications for the generally rising trend in land-falling AR activity found in their analysis based on AR activity for the period 1948 – 2017. Focusing on life cycle characteristics of Pacific Northwest AR, Zhou, Kim, and Guan (2018) distinguish between long and short AR events noting that the former last more than 72 hours and travel 7 times longer in distance and have a stronger intensity than short AR events which last less than 24 hours. Further using life cycle characteristics Zhou, Kim, and Guan (2018) have developed an AR intensity index for hydrological analyses. That the location of AR and where they make landfall holds implications for extreme precipitation events and flooding in the US is recognised in a climatological analysis of the inland penetration of AR over the western parts of the United States. This revealed the Oregon–Washington coast to possess the maximum AR frequency and duration. Minimal AR activity was found for a region extending from the ''high'' Sierra south of Lake Tahoe eastward across the central Great Basin and into the deep interior (Rutz and Steenburgh, 2014). East of the Cascade–Sierra Ranges, Rutz and Steenburgh (2014) found AR frequency and duration to be the greatest over the interior northwest while AR duration is long and frequency low for the interior southwest. Further factors that may well determine the location of AR landfall have been outlined by Hu et al. (2017) who note that amongst two regimes of Rossby wave breaking in the upper atmosphere over the eastern North Pacific AR originating from anticyclonic wave breaks arrive over the west coast from a more westerly direction whereas cyclonic wave breaking-AR adopt a more south-westerly direction in their trajectories.

Compared to the Pacific Northwest, AR for other parts of the United States and the broader Americas have received little attention. For the southeast Debbage et al. (2017) identified the winter months as the time AR are most prevalent, occurring predominately over the Gulf of Mexico. Further a dipole like structure is apparent in AR occurrence across the Gulf of Mexico. For southern California Harris and Carvalho (2018) note that conditions prior to AR making landfall differ from those for the Pacific Northwest with the intra-seasonal to inter-annual variability in AR frequency conditioned on phases of modes of climate variability such as ENSO and the MJO as Debbage et al. (2017) found for AR over the southeast of the United States. For South America, AR landfalls are most frequent over the latitudinal range 38º - 50ºS, occurring on average 35-40 days per year (Viale et al, 2017). North and south of this band AR decrease rapidly as they do east of the Andes. Contributing 45 – 60 percent of the annual precipitation in subtropical Chile and 40 – 55 percent along the mid-latitude west coast, AR for this region exceed the importance for annual precipitation in the Pacific Northwest, most likely due to the severe orographic forcing, achieved under the influence of the Andes (Viale et al., 2017).

Similar to their Pacific counterparts', atmospheric rivers originating over the Atlantic Basin bear implications for westward facing regions north and south of the equator. For the South Atlantic, Blamey et al. (2018) have shown that AR activity along the coast of southern Africa tends to peak in May, early in the winter season, with a subsequent decline over successive winter months; the greatest variability in AR activity also occurs in May. Overall mean AR duration was found to be around 30 hours with about one third of all AR lasting longer than 1.5 days similar to the duration statistics found by Ramos et al. (2015) for AR impinging on the Iberian Peninsula but somewhat longer than that found for some Pacific Northwest AR. With a mean annual AR frequency of 10-11, the South Atlantic possesses similar AR frequencies to that found for the Iberian Peninsula, the United Kingdom and some parts of the Pacific Northwest (Lavers et al., 2012; Nieman et al., 2008; Ramos et al., 2015). Modes of climate variability in the Atlantic sector are effective in modulating the inter-annual variability of AR over the North Atlantic. For the Iberian Peninsula two modes appear important. A positive (negative) East Atlantic pattern, consisting of negative (positive) atmospheric pressure anomalies centred over Ireland and positive (negative) anomalies over north Africa, enhances AR frequencies where as a positive (negative) phase of the Eurasian-Polar pattern supresses (enhances) AR occurrence. For the British Isles Lavers et al (2012) have shown that a negative (positive) phase of the Scandinavian pattern, typified by positive (negative) sea level pressure (SLP) anomalies to the south and negative (positive) anomalies to the north of the British Isles, increases (decreases) the likelihood of AR crossing the latitudinal zone between 50ºN and 60ºN. These findings are largely corroborated by Brands, Gutierrez and San-Martin (2017) in an analysis of AR counts and large-scale circulation indices for the period 1950 – 2010.

4.3 Atmospheric Rivers and Hydrological Extremes

In many ways the type of AR climatologies described above signpost where AR are likely to exert noteworthy hydrological impacts and thus play a role in shaping river flow and fluvial and ecohydrological processes. In this context there is a burgeoning literature on the importance of AR for heavy precipitation events, floods and other hydroclimatological hazards. In a global assessment of the importance of AR, Paltan et al. (2017) estimated that AR contribute 22% of total global runoff, with this reaching 50% or more in some regions and further note that where AR constitute an important climatological feature (are absent) they may increase the occurrence of floods (droughts) by 80% (90%). In order to assess the global significance of AR for precipitation and wind extremes, Waliser and Guan (2017) applied an AR global detection algorithm to reanalysis data for the period 1997-2014. They found that up to 50 percent of the top two percent of precipitation and wind extremes across mid-latitude regions globally, and about 40-75% of extreme wind and precipitation events over 40% of the world's coastlines, were associated with land-falling AR. Waliser and Guan (2017) also note that associated with AR is a doubling or more of the typical wind speed compared to all storm conditions, and a 50-100% increase in the wind and precipitation values for extreme events. With regards to precipitation at the climatological level, Lavers and Villiarani (2015) estimate that 30 – 50 percent of European and US winter season precipitation is contributed by AR especially over their west coasts, but note there is much regional and monthly dependency of this association, while Dettinger (2013) suggests AR are consequential as drought busters. The importance of AR for the cryosphere has also been noted with respect to ablation rates over Greenland (Mattingly, Mote, and Fettweis, 2018; Neff, 2018) and snowfall and ablation in New Zealand (Little et al., 2019), East Antarctica (Gorodetskaya et al., 2014) and the western US (Guan et al., 2013), the transport of moisture and energy to the Arctic Ocean Basin (Hegyi and Taylor, 2018; Villamil-Otero et al., 2018) and climate variability and change in extra-tropical and high latitudes (Nash et al., 2018).

Because heavy precipitation is often a precursor of floods much attention has been focused on the role of AR in the generation of extreme precipitation events. The diagnostic measure employed in assessing this association is usually integrated water vapour transport (IVT) expressed in kg m^{-1} s^{-1} as this has been shown to be closely related to precipitation volumes over complex terrain (Junker et al., 2008). For example over the southeast United States 41 percent of heavy precipitation days (>100 mm day^{-1}) were found to be associated with AR with IVT values in excess of 500 kg m^{-1} s^{-1} (Mahoney et al., 2018). These are comparable to those found over the Pacific Northwest at 400 and 650 kg m^{-1} s^{-1} although values in excess of 1700 kg m^{-1} s^{-1} have been noted for high magnitude AR events here (Dettinger, Ralph and Rutz, 2018). For California, Nieman et al. (2014) note the importance of AR in conjunction with orographic forcing for determining the amount and spatial distribution of precipitation in the northern Sierra Nevada and in the Shasta-Trinity region with precipitation enhancement as AR ascend these coastal ranges. The importance of AR for extreme events across California is also emphasised by Young, Skelly and Cordeira (2017) who outline how floods and debris flows are commonly associated with AR related precipitation extremes during the cold season. Importantly they note warm season flash floods are not commonly associated with AR with convective storms the likely candidates for these. For Chile, Viale et al. (2017) demonstrate that approximately half of all top-quartile precipitation intensities, across subtropical and mid-latitudes, occur under AR conditions with median daily and hourly precipitation in ARs being 2-3 times that of other storms.

The effect of an AR's trajectory and its origin on precipitation outcomes has been emphasised by Ryoo et al., (2016) for the west coast of the U.S. They identify three trajectory types each with their own spatial signature in terms of precipitation distribution. In general, AR events that ascend near landfall and are of tropical origin (AT type), along with those ascending near landfall with an extra-tropical origin (AE type) have more frequent precipitation over a broad region of the western U.S, while AR events composed of both AT and DE types (AR descending or parallel near landfall) have intense precipitation over the south-western U.S. Over north-western US, AT-only AR trajectories produce intense precipitation. Corroborating this distinction between AR trajectories and precipitation patterns is the work of Zhang and Villarini (2018) who note that not all ARs making landfall along the West Coast of the US come from a single population. Rather AR can be stratified in three broad types with distinct precipitation intensity and distribution characteristics.

Over western Europe, especially along the western European seaboard, AR have been found to account for a large proportion of extreme precipitation days with AR exerting hydrological impacts as far inland as Germany and Poland (Lavers and Villarini, 2013). Along with the British Isles (Browning, 2018), Norway is on the front line in terms of AR strikes where Azad and Sorteberg (2017) have shown that 95 percent of extreme precipitation events are associated with narrow plumes of intense low-level moisture in the form of atmospheric rivers. Extensive consideration has been given to the impact of AR on the extreme precipitation (90th percentile above) climatology for the Iberian Peninsula (IP) and the nearby European Macaronesia Archipelagos (Azores, Madeira and Canary Islands) (Ramos et al., 2015, Ramos 2018a; 2018b). For the IP the importance of AR for extreme precipitation rapidly diminishes in an eastward direction with maximum impacts over Portugal and the Minho, Tagus and Duero regions (Ramos et al., 2018a). For the islands lying to west of the IP in the Atlantic Ocean, the greatest impact of AR on precipitation extremes is found for the Azores where around 50 percent of extremes are associated with AR. For Madeira and the Canary Islands, this figure is considerably less (Ramos et al., 2018b). Further afield over southern Asia Yang et al. (2018) note the influence of AR over the Bay of Bengal for northern Indian extreme rainfall events and Kamae et al. (2017) similarly for East Asia.

There is a burgeoning number of studies that demonstrate direct AR – flood associations. For the central United States more than 70 percent of the annual instantaneous peak discharges and peaks-over threshold floods have been found to be associated with AR, particularly during the winter and spring (Nayak, Villarini & Bradley, 2016). Similarly AR play a significant role in generating floods across the western United States where the probability that an AR will generate a given runoff threshold increases significantly when daily mean water vapour transport increases from 300 kg m^{-1} s^{-1} to greater than 600 kg m^{-1} s^{-1} (Konrad and Dettinger, 2018). Acknowledging that there a range of different flood mechanisms due to various meteorological events, Barth et al. (2017) find that AR are mainly responsible for large, regional-scale floods across the western United States with six main areas where floods are AR-sensitive identified. Bearing implications for flood occurrence, the frequency and magnitude characteristics and return periods for AR of varying intensity, as measured by the IVT, have been assessed by Dettinger, Ralph and Rutz (2018) for US West Coast land-falling AR for the period 1980-2016. Derivation of empirical return periods revealed the largest instantaneous IVT in excess of 1700 kg m^{-1} s^{-1}, for AR making landfall between 41ºN and 46ºN, have return periods longer than 20 years with IVT values with similar return periods being lower at around 750 kg m^{-1} s^{-1} to the north and south. For the Waitaki River Basin in New Zealand, ARs located in slow eastward moving extratropical cyclones, with high pressure to the northeast of New Zealand and IVT in excess of 1000 kg m^{-1} s^{-1} have been shown to be associated with major winter floods over the period 1979 – 2012 (Kingston, Lavers and Hannah, 2016). Over the Galicia region of north-west Spain, although most flood events are not associated with AR, the majority of severe flood events, especially in coastal areas in the winter months are; there is more than a doubling of the amount of precipitation in flood events when an AR is present (Eiras-Barca et al., 2018). For the British Isles Lavers et al (2012) have convincingly demonstrated the relationship between AR and winter floods for nine study basins such that the number of peak over threshold flood events associated with persistent AR ranged from approximately 40 to 80 percent across the study basins. With the implications of extreme rainfall events for floods in Britain in mind, Champion, Allan and Lavers (2015) confirm earlier findings of the importance of AR for winter extremes but note that summer extreme rainfall events are minimally associated with AR. For Chennai in India, Lakshmi and Satyanarayana (2019) note the influence of AR in the occurrence of devastating floods.

4.4 Climate Change and Atmospheric Rivers

Defined as narrow corridors of high water vapour flux, atmospheric rivers in a warmer climate are likely to bear implications for future flood hydrology, The physical basis of this assertion is the relationship between saturation vapour pressure and air temperature as described by the Clausius–Clapeyron equation, such that water vapour concentration is expected to rise as a consequence of human-induced climate change and a resultant warmer atmosphere than present. Accordingly under climate change the potential exists for greater water vapour transport via AR (Gimeno et al., 2016) and consequently heavy precipitation due to orographic forcing with an associated change in flood risk for mid-latitude west coasts. Understandably this prospect has spawned a number of assessments of the impact of climate change on AR activity with implications for flooding at a range of scales emphasised. Typically such assessments are undertaken by comparing AR climatologies from empirical observations or historical simulations with future projected AR climatologies from climate models under a range of RCP warming scenarios (e.g. RCP4.5 and RCP8.5).

A burgeoning number of evaluations of AR activity under climate change have been undertaken for North America (Dettinger, 2011; Gao et al., 2015; Hagos et al., 2016; Mahoney et al., 2018; Payne and Magnusdottir, 2015; Pierce et al., 2013; Radić et al., 2015; Shields and Kiehl, 2016a, 2016b; Singh et al., 2018; Warner et al., 2015) and Europe (Gao et al., 2016; Lavers et al., 2013; Ramos et al., 2016; Shields and Kiehl, 2016a). Essentially all show the same thing, an increase in AR activity relative to the present with resultant increases in the risk of heavy precipitation generating floods. While such studies are informative in their own right, especially with regard to a specific area, direct absolute comparisons between these are frustrated by their application of different methods, data sets, and time and spatial domains. In response to this irritation, plus the fact that assessments outside North America and Europe are meagre in number, Espinoza et al. (2018) undertook a uniform global assessment of the response of AR under RCP8.5 for the time domain 2073–2096, using 21 Coupled Model Inter-comparison Project Phase 5 climate models. They found that AR will be around 25 percent longer and wider, and exhibit stronger IVT in the future. Globally this translates to a 50 percent increase in the frequency of AR conditions and a 25 percent increase in IVT strength. For Northern Hemisphere mid-latitudes the increases in frequency and IVT strength are comparable to those at the global level whereas for Southern Hemisphere mid-latitudes, increases in frequency and strength were found to be approximately 60 and 20 percent respectively. In explaining the anthropogenic climate change signal in AR activity and characteristics, the thermodynamic or moistening response of the atmosphere to warming was found to dominate with changes in wind speed (dynamic effects) small in comparison, as found by Lavers et al. (2016) in a general assessment of the determinants of IVT in AR. Lastly and importantly, Espinoza et al. (2018), in undertaking an assessment of future AR behaviour for regions particularly exposed to the impacts of AR (e.g. western United States, north-western Europe, and south-western South America), highlight considerable inter-model differences in projected AR changes thus underlining the issue of uncertainty that plagues a number of assessments of the impact of climate change on flood hydrology and the challenges related to modelling AR related sub-grid scale hydroclimate processes (Doroszkiewicz, Romanowicz and Kiczko, 2019; Gao et al., 2019; Jobst et al., 2018; Meresa and Romanowicz, 2017).

5. Synthesis and Conclusion

This review in the honour of Geoff Petts has focused on three aspects of climate and rivers namely river flow regimes, hydrological variability driven by modes of climate variability and atmospheric rivers. While Geoff may have only worked on flow regimes as one of the dimensions of climate and rivers research addressed here, he always championed the integration of knowledge from cognate disciplines, especially climate, for the purpose of enhancing the understanding and management of river systems and knowledge acquisition on how landscapes 'work' in general terms (e.g. Evans, McGregor & Petts, 1998; Gregory, Gurnell and Petts, 2002; Hannah et al., 2007; Petts, 2009; Petts, Nestler and Kennedy, 2006). Moreover he was always amenable to 'beyond the catchment divide' conversations hence the inclusion of material in this review on modes of climate variability and atmospheric rivers.

Natural flow regimes remain an important concept in rivers research and applications and were of great interest to Geoff Petts (e.g. Boitsidis et al., 2006; Yin, Petts and Yang, 2015; Yin, Yang and Petts, 2012) as they provide a point of reference for understanding the structure and function of a riverine ecosystem and setting ecologically sustainable flows in highly managed river systems (Woods and Petts, 2004). Because the river regime paradigm postulates that riparian and aquatic species are dictated by the pattern of temporal variation in river flows (Lytle and Poff, 2004), there has been much interest in establishing the nature of flow regimes for ungauged basins. While climate classifications have been traditionally applied in estimating flow regimes, recent approaches have moved towards using hydrologically relevant variables as a basis for flow regime classification. A further development in river flow regime research has been the use of Indices of Hydrological Alteration (IHA) to establish the level of impacts on river systems arising from a number of human driven changes, such as water extraction, land use change and dam construction, as well as the state of future flow regimes under climate change. With respect to the latter, both empirical studies and climate model based projections of the impacts of climate change on flow regimes demonstrate strong evidence for a climate driven shift in flow regime type over the last 30 – 50 years for a number of regions as well as fundamental changes in flow regimes under altered temperature and precipitation patterns arising from human induced climate change, a prospect well understood by Geoff Petts (e.g. McGregor et al. 1995). While such empirical and numerical modelling studies proffer a simple climate explanation of altered flow regimes, the so-called attribution problem remains in that a laudable research challenge is the establishment of the extent to which an observed change in the flow regime for a specific water course can be ascribed to natural and/or human factors.

Notwithstanding the importance of understanding catchment scale processes for managing water resources and the ecohydrological health of river systems, large-scale modes of climate variability are increasingly recognised as critical for determining river flow variability through their impact on regional climate variability at a range of time scales. The expanding interest in the impact of climate variability on hydrological systems, especially fluvial and ecohydrological processes, is driven by the prospects of seasonal to inter-annual hydrological forecasting with the improvement of sub-seasonal to seasonal climate forecasting technology, and the prediction of how climate change may alter ocean and atmospheric circulation patterns and thus influence future hydrological outcomes. Here an evaluation of the recent literature has demonstrated the nature of the impacts that periodic alterations in ocean and atmospheric circulation patterns, as manifest by modes of climate variability, can have on hydrological variability. A rich diversity of climate variability modes have been employed in the analysis of hydrological variability such as the SAM, ENSO, the NAO, the PNA pattern, the PDO and AMO. Such modes of variability, as modelled by time series of teleconnection indices, have been applied in hydroclimatological analyses either by default, because they are accepted as the 'go to' descriptors of climate variability, or because sound physical reasoning has been applied in their selection for analysis. While the idea that hydrological variability can be explained simply by knowing the impacts of climate variability is seductive, the imperative to acknowledge the complexity of large scale climate – hydrological variability links is a strong one. For example climate – catchment hydrology relationships are often conditioned on season and region, may be non-stationary or non-linear/asymmetric and vary between concurrent and significantly delayed. Further catchment characteristics are important filters of their hydrological response to recurrent modes of climate variability.

On mentioning the notion of 'rivers in the sky' to some of my catchment based or river channel focused colleagues in the rivers research and applications community, the reaction is often a perplexed one. That said the socialisation of the idea that atmospheric rivers, or fast ribbon-like flows of high water vapour content in the atmosphere, can have discernible impacts on surface hydrological processes is taking root in the hydrology and geomorphology communities (e.g. Garner et al. 2015). Although the term atmospheric rivers entered into the lexicon of hydroclimatologists in the 1990s, the prospect that concentrated jets of water vapour, stretching over considerable distances and occupying significant depths in the lower atmosphere, interacting with rugged coastal terrain and inducing extreme precipitation and flood events has a long precedent (Browning, 2018). Debates aside about the origins of atmospheric rivers, the material touched upon in this review clearly demonstrates their importance as an atmospheric dimension of the hydrology and thus precipitation and flood statistics of westward facing mid-latitude regions. While most empirical and climate change related assessments of atmospheric rivers have focused on the western United States and the western seaboard of Europe it is encouraging to see analyses of this important atmospheric phenomenon emerging for other regions. Beyond extending the geographical focus of atmospheric river studies what awaits the broader rivers research and applications community is explicit considerations of the impacts of 'atmospheric river events' on fluvial processes such as river channel change or ecohydrological stability. Such an agenda, along with efforts to drive forward the understanding of the complexity of the links between large scale climate variability and river hydrology/geomorphology/ecology, that necessarily require the calling to arms of people from across the physical geographical sciences, would have been strongly encouraged by Geoff Petts.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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Figure Captions

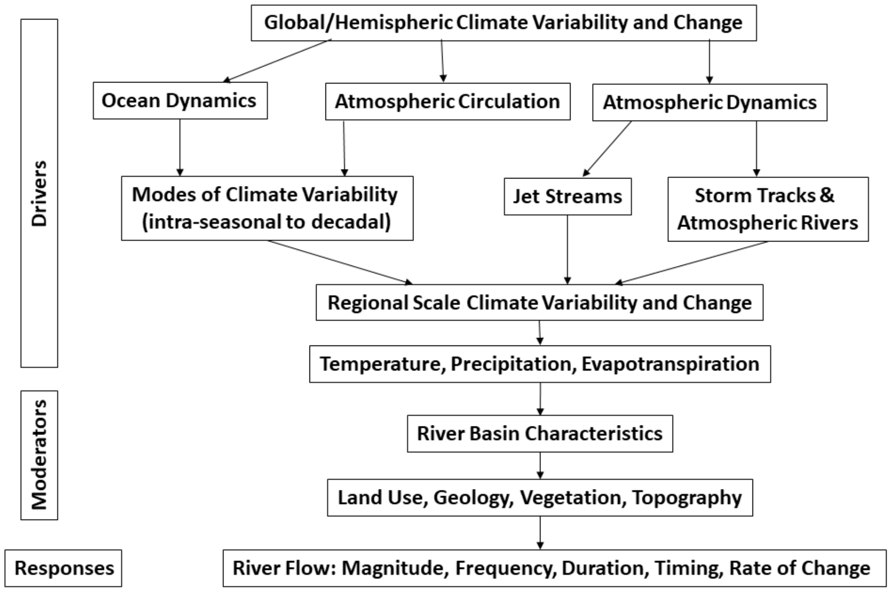
Figure 1: Conceptual model of climate to river basin links, visualising cascade of processes linking a range of atmospheric drivers and river flow response as moderated by river basin characteristics.

Figure 2: Flow regime classification of Knoben et al. (2018) for catchments grouped by climate type. Refer to Knoben et al. (2019) for details of the regime classification. (Source: Knoben et al., 2018).

Figure 3: Ten flow regimes derived by Dettinger and Diaz showing the distribution of proportion of annual flow by month. (Adopted from: Dettinger and Diaz (2000))

Figure 4: Some dominant modes of climate variability referred to in this paper. In the regions where they have their maximum climate impact they explain a considerable proportion of temperature and precipitation variability. Accordingly they possess the potential to influence river flow variability (See Figure 1). PDO = Pacific Decadal Oscillation; ENSO = El Niño Southern Oscillation; AMO = Atlantic Meridional Oscillation; NAO = North Atlantic Oscillation; AO/NAM = Arctic Oscillation/Northern Annular Mode; IOD = Indian Ocean Dipole; PNA = Pacific North American Pattern; SAM = Southern Annular Mode.

Figure 5: An example of an atmospheric river which brought large amounts of moisture to the west coast of England affecting the November 2009 winter flooding in North West England (Source: Earth System Research Laboratory, USA: https://www.esrl.noaa.gov/psd/arportal/)



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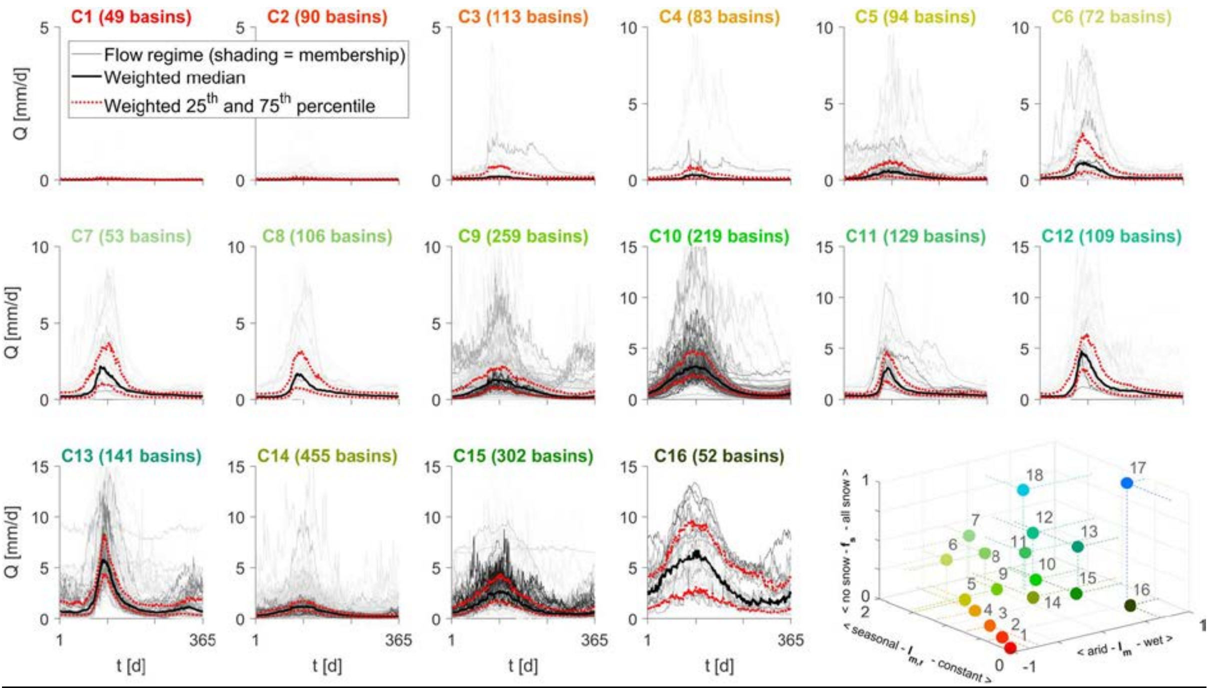

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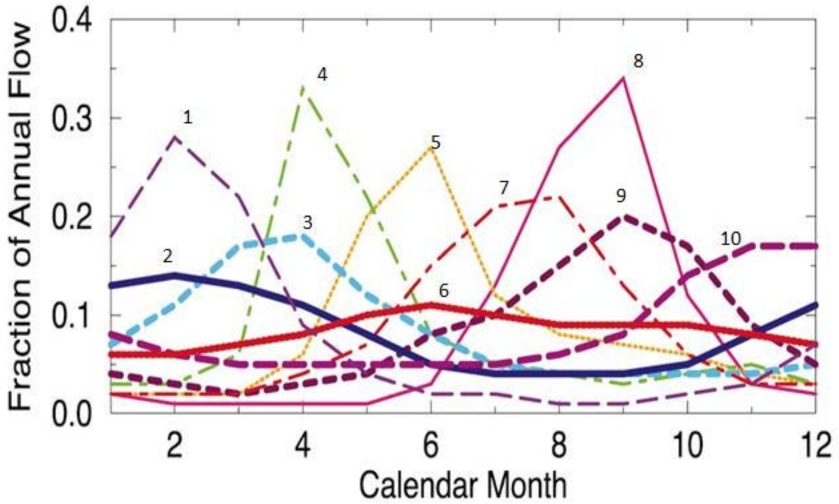

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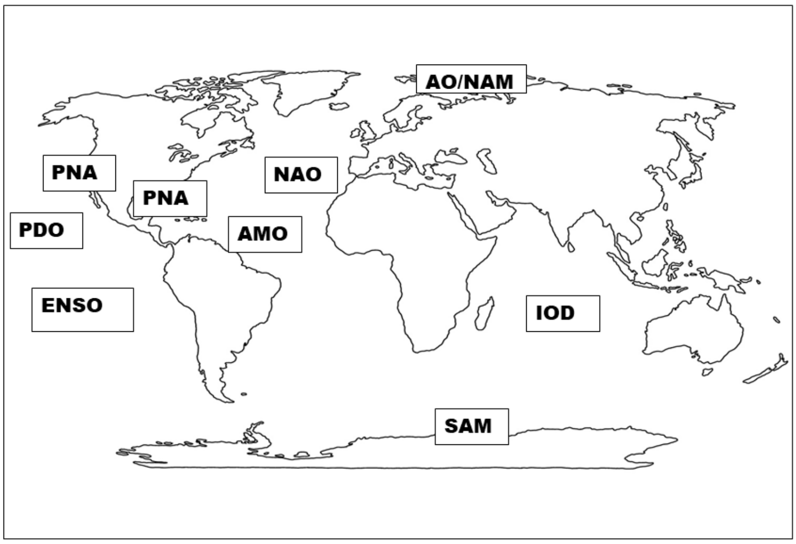

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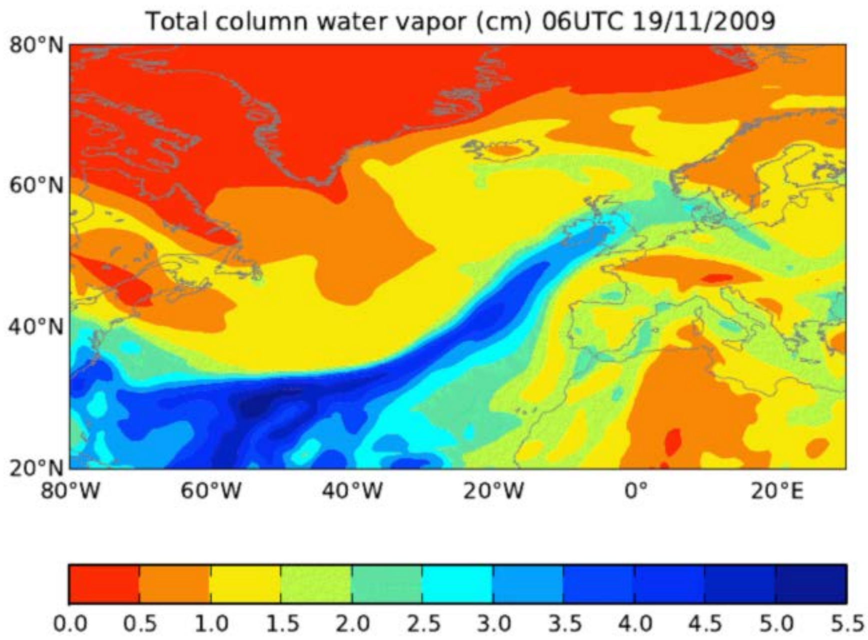

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